

Comparison of Analytical Predictions and Experimental Results for a Dual Brayton Power System

(Discussion on Test Hardware and Computer Model for a Dual Brayton System)

Paul Johnson

*Analex Corporation at
NASA Glenn Research Center
MS 301-2, 21000 Brookpark Road, Cleveland, OH
216-433-3814; Paul.K.Johnson @ nasa.gov*

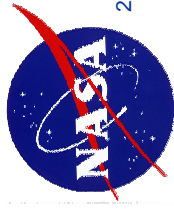
Abstract. NASA Glenn Research Center (GRC) contracted Barber-Nichols, Arvada, CO to construct a dual Brayton power conversion system for use as a hardware proof of concept and to validate results from a computational code known as the Closed Cycle System Simulation (CCSS). Initial checkout tests were performed at Barber-Nichols to ready the system for delivery to GRC. This presentation describes the system hardware components and lists the types of checkout tests performed along with a couple issues encountered while conducting the tests. A description of the CCSS model is also presented. The checkout tests did not focus on generating data, therefore, no test data or model analyses are presented.

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Presented at the Space Technology & Applications International Forum
(STAIF-2007)

24th Symposium on Space Nuclear Power and Propulsion
Albuquerque, New Mexico USA
February 14, 2007

Paul K. Johnson
Analex Corporation
Cleveland, OH 44135
Paul.K.Johnson@nasa.gov



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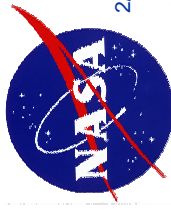
Acknowledgement

The work in this paper was performed for NASA Headquarters, Exploration Systems Mission Directorate. Any opinions expressed are those of the authors and do not necessarily reflect the views of the Exploration Systems Mission Directorate.

The author would also like to thank Bob Fuller of Barber-Nichols.

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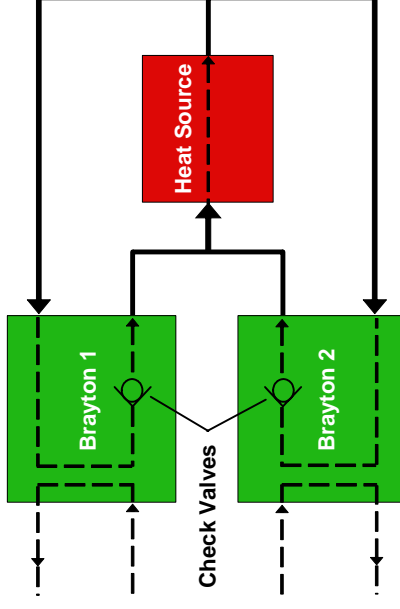
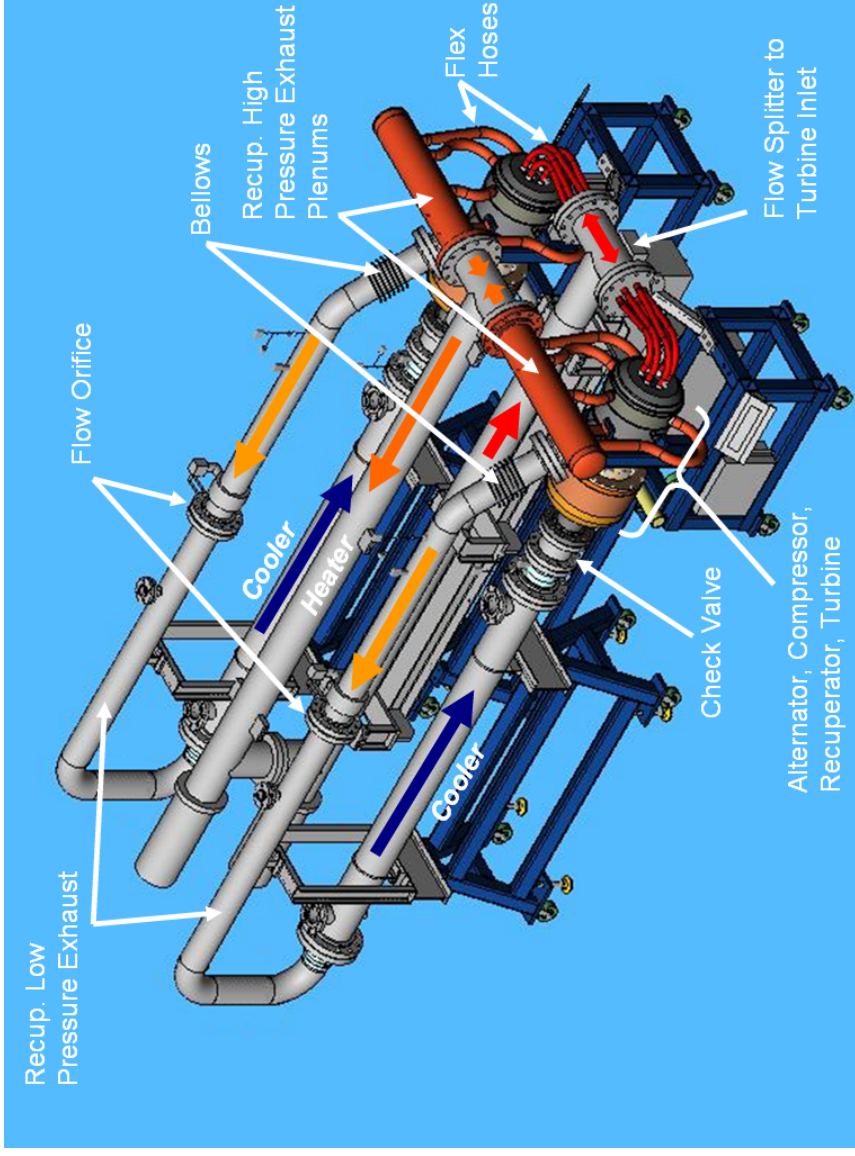
Outline

- Introduction
- System
- Hardware and Operation
- Computer Model Description
- Status
- Conclusions

Introduction

- Recent attention given to gas cooled reactors for potential space power applications
 - No existing hardware to evaluate effect of redundant power conversion units coupled to a gas reactor
 - Experimental studies deemed critical to proof of concept
 - NASA Glenn Research Center contracted for system design and fabrication with Barber-Nichols, Arvada, CO
- A single CBC test loop very similar to this system already exists
 - Also built by Barber-Nichols
 - Resides at Sandia National Laboratories (SNL) and tested by Dr. Stephen A. Wright
- The dual system is unique because it employs two CBC units sharing a common gas inventory and common heat source
 - Working fluid free to redistribute between the two CBC loops as system operation dictates
 - Hardware not flight-like, but sufficient for demonstrating the proof of concept
- Operational areas of interest
 - CBC units at different shaft speeds
 - One CBC unit while the other is standby (i.e. it is off)
 - Starting the CBC units in both staggered and simultaneous fashion
- Parallel computer model development done in Closed Cycle System Simulation (CCSS) design and analysis tool
 - Will be used for pretest predictions and posttest validation
 - Can be employed to make informed decisions for designing future systems

Dual Brayton System

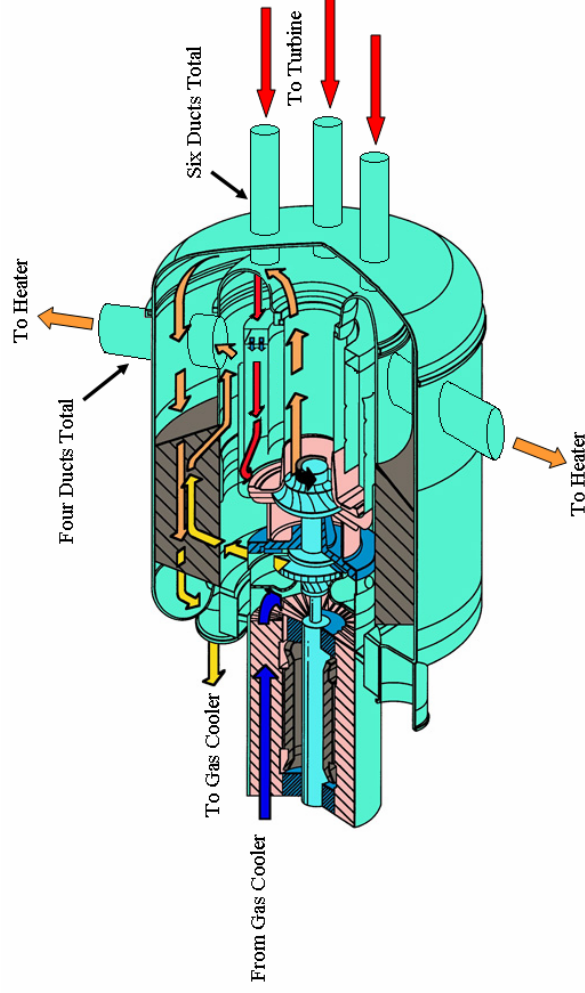
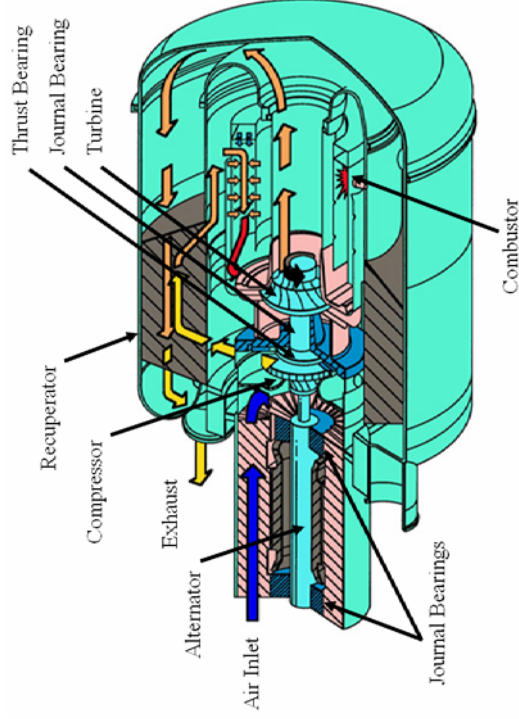


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Modified Capstone C-30

- Centered the design around a modified Capstone Model C-30 commercial microturbine
 - 30 kWe, air-breathing converter
 - Comprises alternator, compressor, recuperator, and turbine
 - Added 4 ducts from recuperator high pressure exit to heater inlet
 - Added 6 ducts from heater exit to turbine inlet



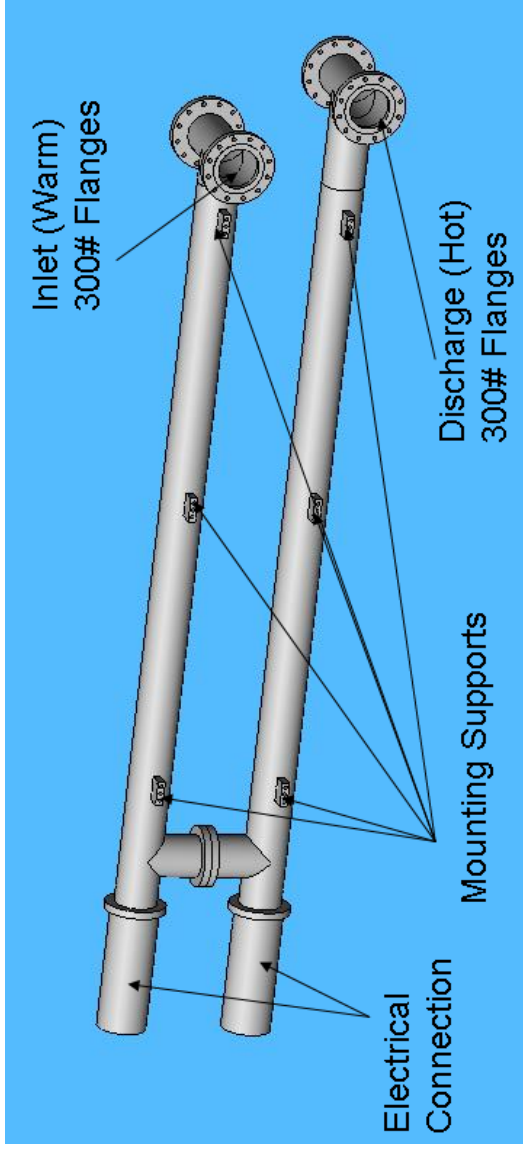
Gas Cooler

- Basco/Whitlock gas-to-liquid heat exchanger
- Shell and tube design
 - Gas flows through 70, 0.5 in. I.D. tubes
 - Water flows through shell side, 8.0 inch I.D.
 - 114 inches long (9.5 ft)



Heater

- Only component shared by the two Brayton loops
- Chromalox – custom built, 180 kW-rated electric resistance heater
 - Maximum achievable gas temperature of 1000 K (Capstones designed for 1144 K)
- Similar to that of a shell and tube heat exchanger
 - 48 heating elements (Incoloy 800) act as the tube portion, 0.475 in. O.D.
 - Series of baffles persuades the gas working fluid across the tubes in the shell portion, 7.98 in. I.D.
 - ~ 300 inches long (25 ft)
- Anticipated 2-3 psi pressure drop at design speed



Assembled Hardware

- The modified Capstone C-30 units, gas coolers, and heater were assembled to form the dual Brayton test loop
- The entire system is 19 feet long, 10 feet wide, and 8 feet high



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System Operation

- Operation requires only a few user control inputs
 - Heat input, heat rejection, and an electric load
- Heater set to maintain a specific power or exit temperature
 - Only one turbine inlet temperature is allowed – one heater
- Waste heat is rejected to the facility water running through the gas cooler
 - Supply temperature is relatively constant for a given day
 - Manual valve is used to control the flow rate of the water
- Retained the Capstone commercial controller, which uses a parasitic load to maintain a set shaft speed
- Computer interface sends command signals to a central controller which communicates with Capstone and heater controllers
- Each CBC loop can be operated at different shaft speed set points
- Certain safeguards in place
 - Capstone controller will not let the shaft over speed
 - Burst disc on each Brayton loop in case of over pressure
 - Heater controller monitors sheath material temperature
 - On-screen warning if compressor inlet pressure is low
 - System shutdown if coolant flow is lost

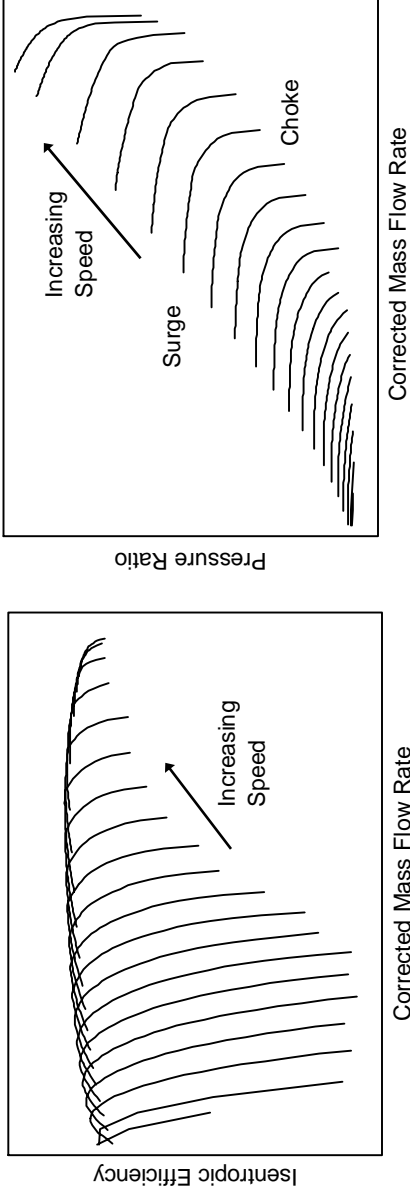
Computer Model

- Closed Cycle System Simulation (CCSS)
 - Numerical Propulsion System Simulation (NPSS) environment
 - Used previously in analytical studies and test hardware performance studies
 - Modeled a flight-like, 2kW Brayton power conversion unit tested at NASA GRC
- Operated in three separate modes: design, off-design, and transient
 - Design
 - Hardware geometries are known and coded into the model setup
 - Off-design
 - Steady-state solutions
 - Vary shaft speed, heater power, turbine inlet temperature, coolant flow rate, gas inventory, etc.
 - Transient
 - Material temperatures become time-dependent
 - Turbomachinery is assumed to operate in a quasi-steady-state mode
- Solver handles 177 independent variables
 - Most of the variables are hardware material temperatures
 - Drive the system to equilibrium
 - All heat transferred is accounted for
 - Sum of the pressure drops/rises around the loop must be zero
 - System gas inventory distributed as necessary

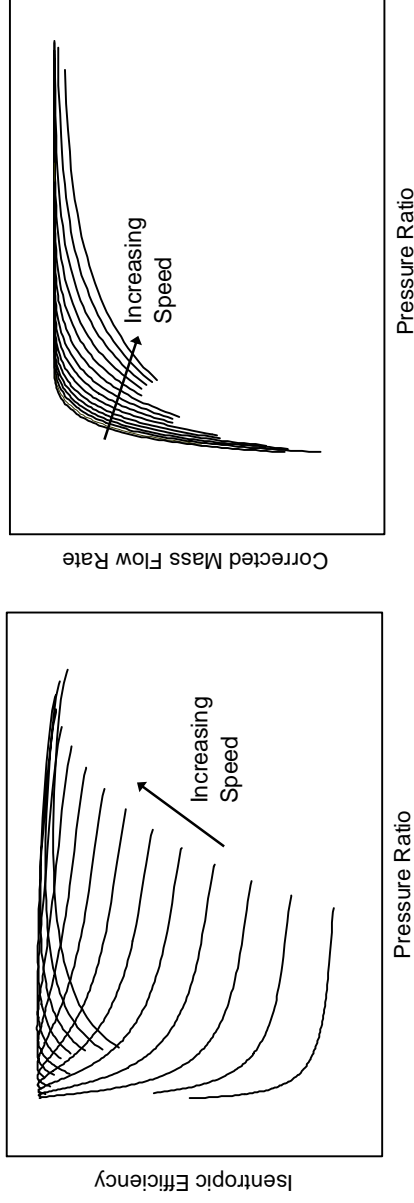
Turbine and Compressor Models

- Compressor performance map generated in CCODP (Centrifugal Compressor Off-Design Program)
 - 10 to 105% design speed
- Turbine performance map generated in RTOD (Radial Turbine Off-Design) program
 - 10 to 155% design speed

Compressor

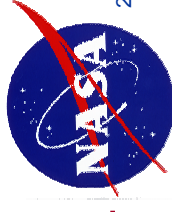


Turbine



Pressure Ratio

Pressure Ratio



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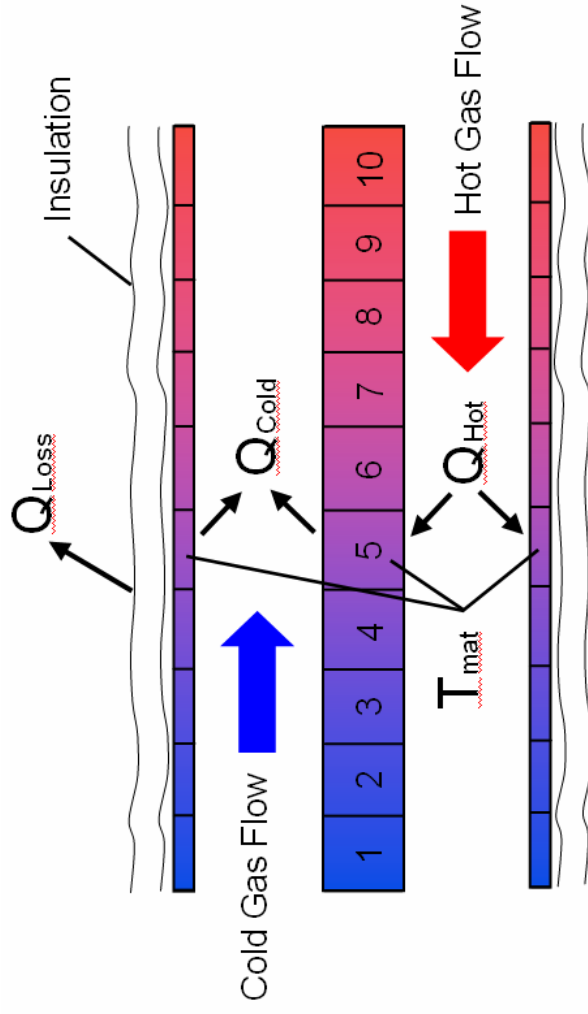
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Recuperator Model

- Gas-to-gas, offset strip-fin, counter flow heat exchanger ~ 78% effective
- Kays and London heat transfer and friction factor coefficients
- Structure is divided into ten nodes – stainless steel
- Heat loss across the insulation is always calculated as steady-state

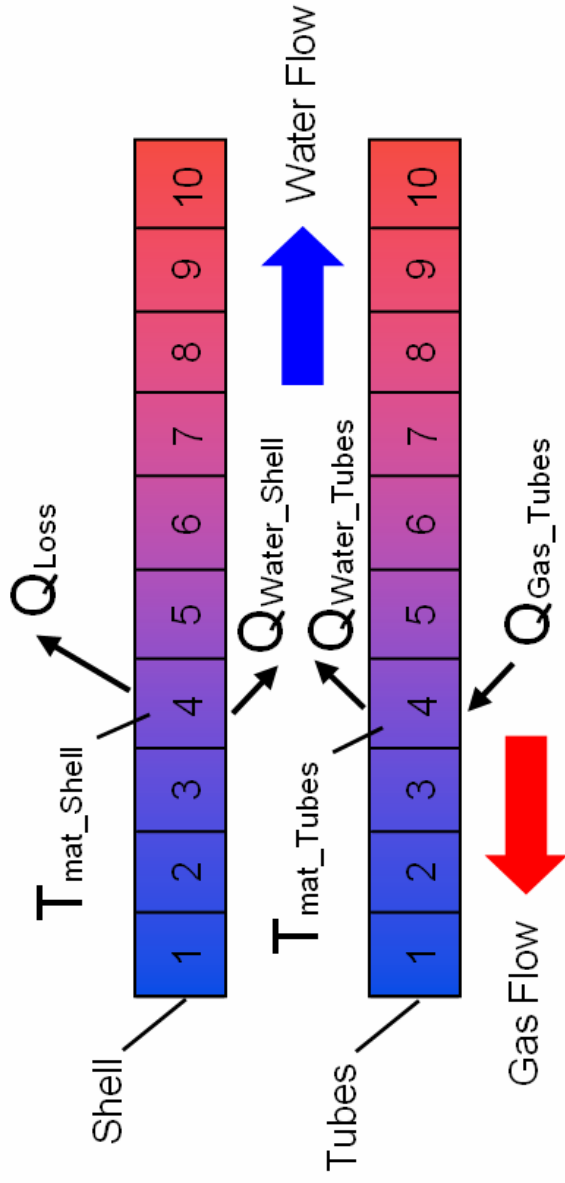
$$\dot{Q} = h_c A (T_{mat} - T_{fluid})$$

$$\frac{dT_{mat}}{dt} = \frac{Q_{in} - Q_{out}}{m_{mat} C_{mat}}$$



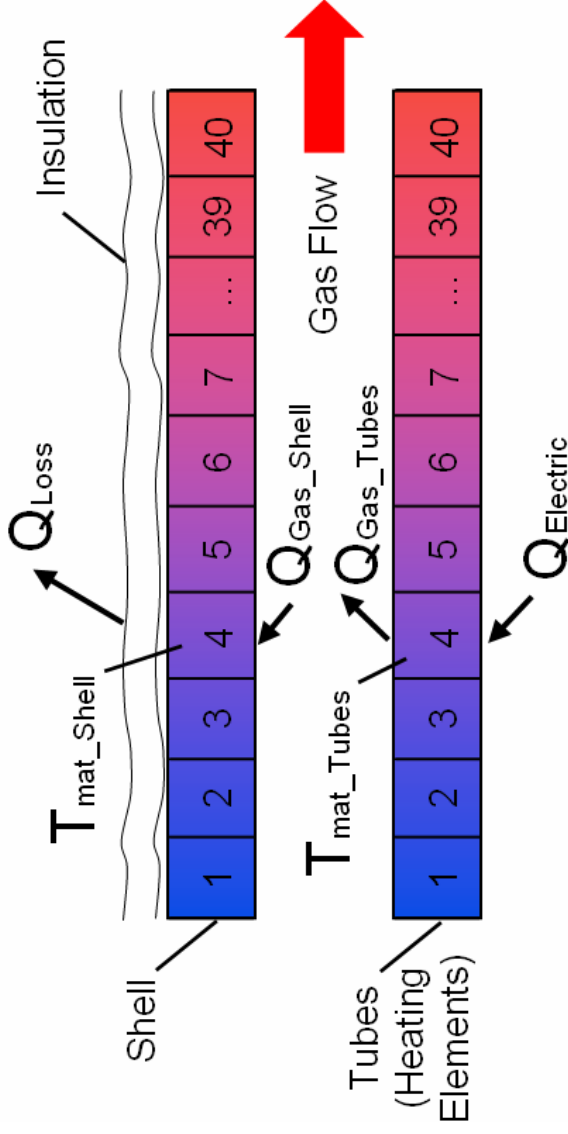
Gas Cooler Model

- Shell-and-Tube, gas-to-water heat exchanger
- Circular pipe flow correlations for heat transfer and friction factor coefficients
- Structure is divided into ten nodes – stainless steel tubes, carbon steel shell
- Heat loss to ambient air, but no insulation



Electric Heater Model

- Shell-and-Tube like electric resistance gas heater
- Modified circular pipe correlations for heat transfer and friction factor coefficients
- Structure is divided into forty nodes – Incoloy 800 heating elements, stainless steel shell
- Heat loss across the insulation is always calculated as steady-state



Status

- Checkout tests performed at Barber-Nichols
 - Individual units ran as single loop with second unit blanked
 - Staggered and simultaneous dual system startups
 - Ran dual system at equal and unequal speeds
 - Heater power limited at Barber-Nichols facility
- Current issues with system hardware
 - Internal flow leakage in the Capstone units
 - Recuperator HP exit to turbine inlet/exit
 - Recuperator bypass flow at housing
 - Resolved through installation of internal manifold
 - Heater pressure drop much greater than design specification
 - Anticipated 2-3 psi drop, measured >3 psi at half speed, estimate >10 psi at full speed
 - Working with Chromalox to resolve the issue
 - Proposed solution to reduce number of internal baffles
- Expected delivery to Glenn early Spring

Conclusions

- Built a dual closed-Brayton-cycle system with common heat source and common working fluid
- Demonstrated the ability to startup and shutdown units independently
- Demonstrated operation with speed imbalance
- Need to resolve heater pressure drop issue
- Will compare test data to model analysis